Characterising the actual performance of domestic mechanical ventilation and heat recovery systems

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ABSTRACT

This paper describes the findings and recommendations of a meta-study examining the actual in-use performance of whole-house mechanical ventilation heat recovery systems (MVHR) installed in 54 low energy dwellings in the UK, as part of a national research programme. The performance of the systems is assessed using monitored data on indoor air quality (temperature, relative humidity, CO_2) and energy use, cross-related with actual experiences of operating these systems through resident surveys. Design/research team interviews were also used to ascertain the reasons for selecting MVHR as a ventilation strategy for a housing development. Cross-analysis of the quantitative and qualitative data helps to identify the key features of MVHR systems with respect to quality of design, installation and commissioning procedures.

Overall the study indicates that the rationale behind the use of MVHR systems is borne out – the rates of ventilation as evidenced very generally by CO_2 levels are better, and the energy use overall is lower. However the study also highlights the prevalence of sub-optimal systems and the possible implications on both energy efficiency and indoor air quality. This would lead to houses being naturally ventilated, but relying entirely on opening windows where there is no provision for background ventilation. In some spaces where this is not possible (for example due to external factors such as noise or security), or where there is less adaptive behaviour (for example bedrooms overnight), very poor levels of ventilation are experienced.

In general the energy consumption in houses with MVHR systems was lower, but this needs to be contextualised – 77% of the MVHR dwellings with energy data were of Passivhaus construction, which in general have lower consumption within the domestic sample (albeit with MVHR as a key component). In some cases it was found that MVHR systems were selected to achieve compliance with the Code for Sustainable Homes, without much understanding of required air-tightness of the building envelope or the maintenance requirements of these systems. Key recommendations include better understanding of the design issues to ensure good airflow and avoid installation problems associated with ductwork; designing in maintenance requirements including unit location, filter cleaning and replacement; ensuring good communication of the design details with installers and commissioners in conjunction with better quality control onsite; along with improved handover processes and occupant guidance.

KEYWORDS

MVHR, indoor air quality, Passivhaus, meta-study, building performance evaluation

1 INTRODUCTION

There is growing evidence that decarbonisation strategies aimed at the housing sector do not always achieve intended results and this performance gap between ‘as designed’ and ‘as built’ is increasingly common in findings (McGill et al., 2017, Gupta and Kapsali, 2014). To address this, Innovate UK (formerly the Technology Strategy Board) commissioned the Building Performance Evaluation (BPE) programme in 2010. A key aim of the programme was to identify the causes and scope of performance gaps across a wide range of high-performance buildings. This was a 4-year programme to support a range of BPE studies across the UK in both domestic and non-domestic buildings. There were two phases to the programme. Phase 1 studies looked at post-construction and early occupation only; Phase 2 studies undertook Phase 1 evaluation but also in-use and post-occupancy monitoring and evaluation over a 2-year period.

With improved fabric-thermal performance, ventilation losses become more significant and strategies that can reduce these may carry considerable weight when evaluating proposed performance. As a result, mechanical ventilation with heat recovery (MVHR) is an attractive option for improved performance standards. Consequently, the uptake of MVHR systems is on the rise, with these systems expected to become a common form of ventilation in the coming years. Therefore, considering the high-performance standards (such as Code for Sustainable Homes (CSH) and Passivhaus) of the BPE dwellings, it was apparent from the start of the programme that a significant number of dwellings were using MVHR systems. The ability to provide requisite levels of ventilation, whilst maintaining energy efficiency is a highly desirable goal, but a move away from traditional and familiar forms of ventilation is a step-change in UK housing design. These systems (combined with appropriate air tightness) are expected to reduce space heating demand, improve indoor air quality (IAQ), and improve thermal comfort (AECB, 2009, Banfill et al., 2011); however, with increasingly mainstream use, a series of studies have also highlighted significant concerns regarding the specification, installation, commissioning, performance, operation and maintenance of MVHR systems in a domestic context (Gupta et al., 2013). Appropriately therefore, among the many requirements under the BPE programme, the review of systems design and implementation included the review of installation, commissioning and measurement of performance and energy use of MVHR systems.

This paper describes the findings and recommendations of a meta-study examining the actual in-use performance of MVHR installed in low energy dwellings in the UK, as part of the national BPE research programme. This meta-study was commissioned by Innovate UK to undertake a broad assessment of domestic projects that utilised MVHR systems. The aims of the study were to identify the nature of MVHR systems, to analyse the available performance data, to gather information and insights from projects about the issues affecting the use and performance of these systems, and to share this information, experience and knowledge both within projects and to the wider construction industry. Whilst projects have undertaken individual assessments of performance, this study provided an opportunity to make a broad comparison across a range of projects, to identify common issues and to make a comparative analysis of the use of these systems.

1.1 MVHR in practice

Several studies have been published on the expected and resultant performance of MVHR systems in new and retrofit dwellings across a number of countries. Common faults among dwellings with MVHR appear to be oversupply of heat, unacceptable noise levels, dirty systems, etc. stemming from poor planning, lacking design support, poor installation and commissioning. In addition, poor or non-existent occupant support for optimal use results in negative impacts on the energy and IAQ against design expectations. Gupta and Kapsali (2014) showed through BPE results that six dwellings in three different developments in the UK were built with final air permeability above that which warrants the need for MVHR. Poor installation and commissioning of the systems were also found to be highly problematic in all six dwellings due to lack of experience with the systems. These failures led to increased heat loss and heat loads, increased energy consumption, unacceptable noise, and cold draughts. Lack of knowledge regarding the systems also resulted in inaccessible controls, where most negative feedback from occupants related to operation and control of the systems.

Balvers et al. (2012) also demonstrated installation and commissioning failures in 150 homes in the Netherlands: half of homes had unintentional recirculation of exhaust air; many systems internally polluted with dust and dirt found in the air supply ducts of about 66% of the homes; half of the homes had no bypass on the heat exchanger; and more than half of the homes had noise levels from the systems that exceeded the reference value, especially in bedrooms.

McGill et al. (2015) demonstrated occupant lack of knowledge on how to operate the system and change filters. Likewise, Sodagar and Starkey (2016) concluded through monitoring and evaluation of MVHR systems in social housing designed to CSH Level 5 that occupant misunderstanding of how to operate controls of the MVHR system can undermine the energy benefit and purpose of the system. In response to the many issues with MVHR demonstrated in research, White et al. (2016) recommend education and training throughout the supply chain to ensure high quality MVHR installation which is critical for optimum system performance. In addition, Gupta et al. (2013) recommend well timed, phased training with hands on demonstration and visual and simple yet comprehensive guides to help occupants understand these complex systems. Also with regard to whole–system design, management and delivery of thermal comfort, Berge et al. (2016) showed through simulation and POE, of Passivhaus apartments in Bergen, Norway, that a uniform supply of heat recovery temperature throughout a dwelling using single-zone MVHR resulted in oversupply of heat in bedrooms. In addition, the observed response of increased window ventilation to lower the temperature in bedrooms did not completely resolve thermal comfort concerns and lead to an overall increase in space-heating demand. Toledo et al. (2016) demonstrated that the greatest propensity to overheat was in dwellings with MVHR. These findings show that much improvement is needed to deliver the expected benefits of MVHR systems in dwellings.

2 METHODOLOGY

From the 3000+ dwellings funded and built through the BPE programme, there were a total of 237 MVHR ventilated dwellings. The dwellings come from a range of development sizes, one-off through to major developments (largest ~790 dwellings). There was wide geographical spread of MVHR ventilated dwellings (from Edinburgh to Exeter and Northern Ireland to the east of Greater London) that are included within this study. Detailed investigations were only typically performed on a few dwelling from each development. This study involves 54 dwellings (54 MVHR systems); located in 29 developments (i.e. domestic BPE projects). Care was taken to ensure that both mainstream low energy housing and Passivhaus projects were represented in the sample. Out of all the dwellings assessed in this meta-study, 20 are certified Passivhaus properties. To enrich the study, a further 15 non-MVHR (MEV or naturally ventilated) dwellings have been assessed for environmental performance, and this has been used to benchmark performance against these two principle ventilation strategies. The meta-study involved both quantitative and qualitative data. Quantitative data included air flow rates, commissioning data, temperature, relative humidity (RH), CO_2, and energy consumption. Qualitative data covered resident satisfaction, comfort, control, etc. from the Building Use Survey (BUS)[1] Methodology© (27 projects) and surveys and interviews with design team or BPE research team (from this point ‘BPE team’) representatives (15 projects) selected based on the willingness to get involved with qualitative review. A summary of data features and properties reviewed is provided in Table 1.

Table 1: Summary of properties reviewed

Dwelling	Performance	BPE team	Temp / RH data	BUS survey	CO_2 data	Energy

[1] The BUS methodology is an established way of benchmarking levels of occupant satisfaction within buildings using a structured questionnaire where respondents rate various aspects of performance on a scale of 1-7.

types	characteristics	interviews				
MVHR	54 homes	15 projects (163 homes)	35 / 36 living rooms 39 / 45 bedrooms	27 projects (211 homes)	22 living rooms 23 bedrooms	39 homes
Non-MVHR	n/a	n/a	17 / 17 living rooms 24 / 24 bedrooms	15 homes	15 living rooms 24 bedrooms	20 homes
(source)	BPE reports	Primary	EMBED	Innovate UK	EMBED	DomEARM

Final reports and detail sheets were reviewed to create standardized characteristics forms identifying system and dwelling data characteristics (e.g. system balance). The original commissioning data was available for 38 out of the 54 systems reviewed. Design air flow rates were available for 43 systems and measured air flow rates were available for 52. Assessments have been made for each system to determine their success for meeting both their original design air flow values, and for meeting the design specification published in Approved Document F – Ventilation (AD F: Part F of the Building Regulations for England and Wales). Some dwellings within the portfolio are located in Scotland and Northern Ireland, where different regulations are used. However, for the purpose of this meta-study, comparisons have been made with the design guidance published in AD F, irrespective of dwelling location. AD F, which carries the same specification as Technical Booklet K (Building Regulations (Northern Ireland)), and Building (Scotland) Regulations (Technical Handbook - Domestic Section 3 Environment), does not contain any performance specification for dwelling air flow rates.

Environmental data (max, min, mean and range) generated within the EMBED[2] platform formed the basis of the indoor environmental analysis. Cleaning of the data was performed within the EMBED platform, where data greater than two standard deviations from the median was classified as 'in error' and was not used in the calculations. Analysis of environmental data was limited to three months (February, April and August), representative of winter, spring and summer conditions. This provided the opportunity to explore seasonal variations. The analysis was further limited to the year 2013, to reduce the impact of yearly climate variations. Monitoring sites were limited to living rooms and bedrooms, as these tend to have the greatest levels of occupancy. Although energy data was available on the EMBED platform, this was significantly limited and there were a number of caveats pertaining to the validity of the available information. Therefore, energy data (annual space heating, electricity consumption and non-electricity consumption) was instead extracted from the available Domestic energy assessment and reporting methodology (DomEARM) datasheets. Unfortunately, it was not possible to accurately evaluate the electrical consumption or heat recovery efficiency across the range of MVHR systems in practice due to a lack of data.

The purpose of the reanalysis of BUS surveys, surveys and interviews by the BPE teams was to contextualise the physical data; understand the design intention and expectation of the MVHR systems; identify problems and good practices in terms of specification, maintenance or operation; and to evaluate how occupants interact with MVHR systems and how this may impact on their performance. Feedback from occupants was assessed by undertaking a re-analysis of BUS survey results (n: 27 projects covering 211 dwellings) along with primary data collection using online survey questionnaire and/or telephone interviews with BPE teams (n: 15 projects covering 163 dwellings). Nearly half of the projects subject to survey were Passivhaus projects. The remaining projects were split between UK, Northern Ireland, and Scottish building regulations, and CSH 4 & 5.

3 RESULTS

[2] Monitoring data recorded by sensors and meters in each Phase 2 dwellings has been uploaded onto an online central data repository, owned and operated by Innovate UK, known as EMBED (www.getembed.com/).

3.1 Design, installation and commissioning

Overall, for the majority of the projects in which BPE teams were interviewed or questioned, the design intention for including an MVHR system was to provide acceptable IAQ in the homes. Code compliance was also a driver for installing MVHR systems. However, according to BPE team interviews, three (20%) of the projects had MVHR systems installed that were not the same as-designed and six (40%) of the respondents were dissatisfied with the installer's procedures, competence and the quality of the ductwork installed. On the other hand, not one respondent (willing or able to comment) was explicitly dissatisfied with the coordination on site during construction. Most satisfaction with as-installed systems was with the location of the outlet terminals and the accommodation of the system within the structure of the dwellings. The majority also found the ductwork to be sufficiently insulated and door undercuts to be provided where necessary. Above all, the maintenance regime of the system was considered to be the most poorly planned aspect of the process.

Achieving a reasonable balance between supply/intake air streams and extract/exhaust air streams is important for heat recovery with an MVHR system. An imbalance can put the dwelling under a slight pressure differential, which in turn will allow ventilation air to find alternative air paths via the building envelope. This will likely have a bearing on the system heat recovery efficiency. AD F (2010) does not set imbalance criteria; the maximum allowable imbalance between intake and exhaust air flow in the Passivhaus criterion is 10%. A slightly more relaxed allowance of 15% is taken as current accepted practice, although there is no known publication of this value. Figure 1 shows the balance observed in 52 MVHR systems set at 'normal' speed. These values are taken from the sum of the individual room supply and extract rates, and not the intake and exhaust measurements, as these were not available in most cases. The red dotted line shows the 15% allowance. Out of the 52 systems, 25 (48%) have an imbalance of <15%, the remainder being above this, with 14 (27%) being significantly out of balance (deemed as >30%). Of the 15 Passivhaus systems, 6 show an imbalance of >10%.

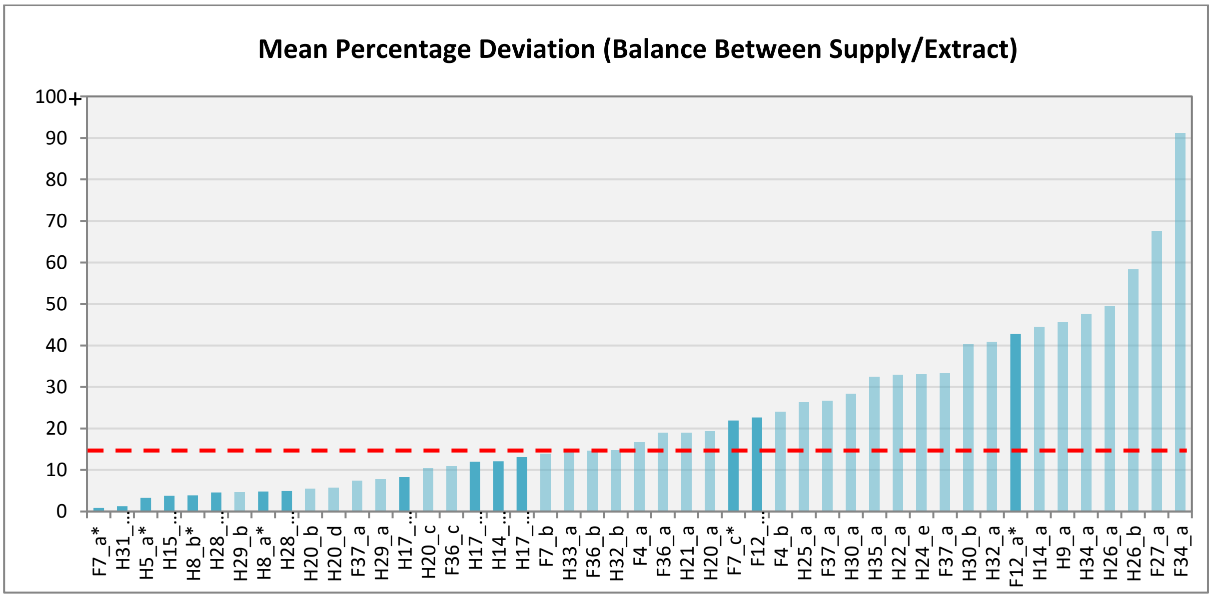

Figure 1. Symmetrical mean percentage deviation between supply and extract rates
** against dwelling reference denotes Passivhaus.*

With regard to air flow rate requirements 23 of 34 systems (68%) designed under AD F (2006) met the minimum requirement in reality and six of 18 systems (33%) designed under AD F (2010) met the minimum requirement. The original commissioning data was available for 38 out of the 54 systems reviewed. Of these, only 19 were reported to be commissioned at both normal and boost speeds. Thus, 50% of the systems can be judged to be only partially commissioned with respect to air flow. Out of the 38 sets of commissioning data reviewed, only 6 (16%) systems have provided sufficient evidence to demonstrate that they have been satisfactorily commissioned with respect to minimum air flow rates and balancing. Likewise as per design interviews, the most common problems at the installation or commissioning stages include imbalance between supply and extract airflows, poor installation and (likely as a result of the former problems) the system had to be recommissioned in one-third of the projects. Interviewees specifically described installation and commissioning issues including: system imbalance (n. 3), no airflow in some supply lines (n. 1), blockage/restricted/crushed ducts (n. 2), uninsulated ducts (n. 1), and development with dwellings ranging from flats to three bedroom homes found to have identical fan speeds (n. 1).

3.2 Handover and use

According to the BPE teams, the dissatisfaction among occupants with the MVHR system is mainly due to inadequate understanding of how to use, operate and control the system, indicating inadequate handover, training and/or guidance. Furthermore the respondents felt that although the majority of the occupants were aware of the purpose of the MVHR and where the essential controls and displays of these systems were located, there was a lack of understanding of what the controls and displays are meant for and actually do. According to the BUS results, the occupants felt that they had a higher level of control over ventilation than the BPE team perceived them to have. The BUS response can however, include the ability to open windows and from the point of view of the respondent they may not consider the MVHR system alone as a source for ventilation control.

The design/research respondents felt that the most common operational issue with the MVHR systems for occupants was maintenance of the system. As an example, in a number of cases, the MVHR system is not easily accessible for occupants, precluding occupant led maintenance in most cases. Evidence of occupants disabling the system was split down the middle. Half of the sampled projects had occupants that did not disable the system and of the half that did, the most common reason was out of concern for the operating cost of the MVHR. There appeared to be a lack of trust and understanding in the need for the system. Most often the assumption that the MVHR system was the highest consumer of electricity was also wrong. Other reasons included draughts, noise, and misunderstanding appropriate management of the system. It is apparent however from the interviews that the Passivhaus projects investigated had fewer performance issues than the non-Passivhaus dwellings, particularly with regard to draughts or other discomfort and high temperatures (figure 2). This difference in performance between the Passivhaus and non-Passivhaus dwellings may be in part to the level of detail and planning required for a Passivhaus as a whole system.

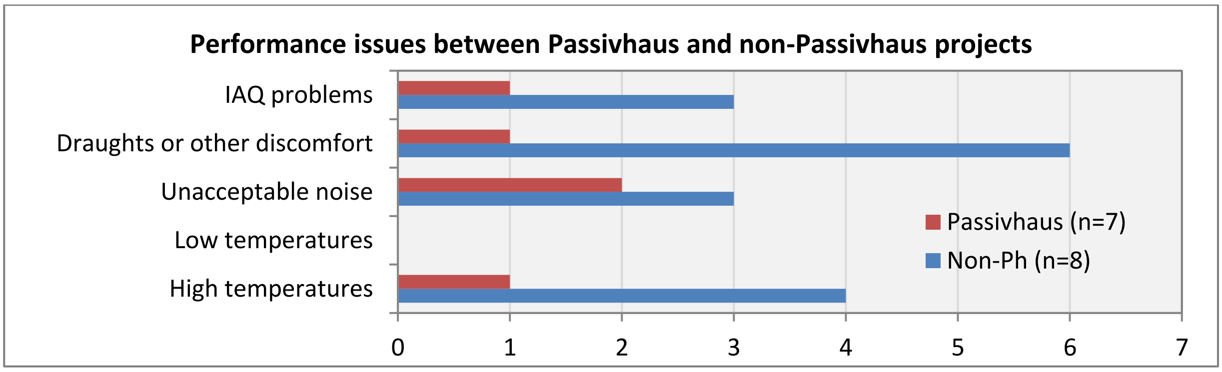

Figure 2. Performance issues

3.3 Energy and indoor environment

Metered data indicates that the space heating demand was generally lower in dwellings with MVHR systems. There were of course a few exceptions to this. Table 2 shows the mean annual energy consumption among the MVHR and non-MVHR dwellings analysed. It is important to note that airtightness levels, construction type and space heating strategies are likely to have significantly influenced these results. The findings show that homes with MVHR systems generally consumed less energy than homes without MVHR systems; however, it is important to emphasise that the majority of monitored MVHR dwellings were Passivhaus certified and given the stringent energy requirements of the Passivhaus certification method, this is likely to have had a significant impact on the results.

Table 2: Annual energy consumption (MVHR vs Non-MVHR)

	Electricity (kWh/a)	**Electricity (kWh/m2/a)**	**Non-Electricity (kWh/a)**	**Non-Electricity (kWh/m2/a)**	**Total Consumption (kWh/a)**	**Total Consumption (kWh/m2/a)**
MVHR (n=39)	3320.6	40.3	3689.8	46.5	6918.2	85.6
Non-MVHR (n=20)	3025.0	38.2	8611.2	113.3	10201.0	132.6

There is a clear differentiation in CO_2 levels between the dwellings with and without MVHR systems, with MVHR systems in general having lower levels of CO_2. The difference is more marked when comparing peak CO_2 levels in living rooms and bedrooms, which were noticeably higher in the non-MVHR dwellings (Figure 3).

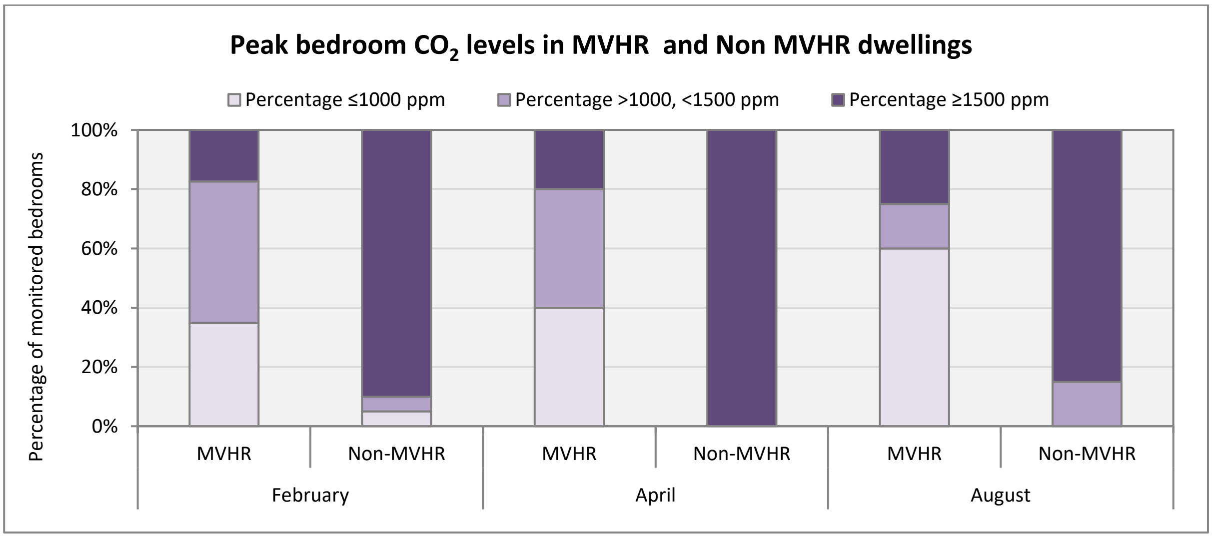

Figure 3. Peak Bedroom CO_2 levels in MVHR and Non-MVHR homes

Both peak and average levels were higher in the bedrooms and in these spaces the difference was much greater in non-MVHR houses. According to the mean BUS results from 10 of the 15 projects, satisfactory levels of IAQ were achieved both in summer and winter. This supports the fact that occupants in only four of the 15 projects (27%) reported IAQ problems to the BPE teams interviewed. The impact of ventilation provision on indoor CO_2 levels was most evident during February, which is likely due to a lower prevalence of window opening during the winter season. However higher CO_2 levels were also found in general in non-MVHR compared to MVHR dwellings during both April and August months, but in the summer the picture is more mixed, with more MVHR houses with higher CO_2 levels. This may be due to a shift toward natural ventilation strategies in summer with greater window opening, but may also be due in some cases to MVHR systems being turned off in summer. This comparison may indicate that the homes with MVHR systems achieved a better ventilation outcome compared to non-MVHR homes and, specifically, that the use of an MVHR system may have attributed to improvements of ventilation levels in these homes.

One of the potential consequences of ventilation performance is the impact on moisture in the buildings. Ventilation rates set in regulations are primarily designed to control moisture (rather than a more general requirement of IAQ) so a comparison may be made of RH levels in MVHR and Non-MVHR dwellings. In general RH levels were within reasonable ranges, tending toward the lower end. The average and minimum living room and bedroom RH levels (during February, April and August) were generally higher in dwellings with MVHR systems but were not at unduly extreme levels. In general, RH levels were more stable during all monitored seasons in the MVHR houses and this trend was particularly evident during winter. Highest RH levels were seen in August with 35% of MVHR dwellings recording peaks > 60% RH. As indicated by the CO_2 data this suggests high rates of window opening. On the other hand, it is apparent that low RH is common in MVHR dwellings during the heating season.

An observation of temperature data is that, in general, average temperatures were higher in Non-MVHR dwellings during February and April, but higher in MVHR dwellings during summer. As with the data on RH, an apparent trend is for houses with MVHR systems to have greater temperature stability, with a greater dispersion of indoor hygrothermal conditions found in dwellings without MVHR systems. The temperatures observed in the MVHR dwellings were closer to optimal conditions. This may be affected by the prevalence of Passivhaus dwellings in this cohort, but may also be due to poor performance in non-MVHR houses which may have oversized and poorly controlled heating systems. In summer a differentiation between MVHR and non-MVHR was less clear, with some MVHR houses having very high peak temperatures. Whilst the overall trend for MVHR houses is positive, there are outliers where conditions are poorer. Without detailed occupancy data and external weather data, it may not be applicable to compare measured indoor temperatures with comfort criteria. Nevertheless, it is important to highlight that average temperatures exceeded 25°C (Passivhaus overheating criteria) during August in 18% of MVHR bedrooms, with peak levels exceeding 28°C in 11%. Correspondingly, in the monitored living rooms, average temperatures exceeded 25°C in 31% of MVHR dwellings during August, with levels peaking above 28°C in 16%. These results suggest issues with summertime overheating in a number of the MVHR dwellings. This may be attributed to a lack of summer by-pass capabilities in some homes, or systems being disabled in the summer, which is also suggested by the CO_2 and RH data. Whilst this may be expected, or indeed planned, it raises questions about the effectiveness of this in certain rooms which may be less tolerant of window opening due to issues of noise or security.

4 DISCUSSION

The paper has described a number of problems and issues encountered, evidenced both from the characteristic data and feedback from designers and occupants. These included lack of complete commissioning, poor air flow and extract rates (and associated lack of compliance with regulatory standards), lack of balance and inappropriate duct types. There was also a lack of consideration of key issues at design and construction stages, including the function of the system, integration into the design, quality of installation and commissioning, control systems, and occupant guidance and understanding. Poorly conceived and designed systems are difficult to install, difficult to maintain and difficult to use. The need for systems to be correctly selected, specified and designed could reduce many subsequent issues. Particular considerations include: unit location in terms of ease of installation and subsequent maintenance regime.

The study found a lack of Building Regulation compliance to be commonplace, and this is a cause for concern, particularly given the potential health impacts of under-ventilation. It is clear that a more rigorous commissioning and compliance checking regime is needed which may lead to increased onsite inspections by building control, but also warranty providers. There is a need for improved skills in the construction industry. One of the observations is the different trades that might be involved in the installation of a system, including plumbers, joiners and electricians, and there is a lack of oversight at installation stages. Although some improved guidance is available (for example NHBC Standards Chapter 3.2 'Mechanical ventilation with heat recovery', further improvement is needed, for example protection of ductwork during construction and on-site inspection to ensure compliance with these standards. The study found some issue with commissioning tests, and more rigour is required to ensure that such tests are undertaken to required standards. An issue arising with commissioning is subsequent interference with room supply air terminals, for example to reduce air movement. This may be addressed by having vents which can be locked or marked in place; better occupant guidance about the nature of the vents; or alternative (or variable) flow regulation systems. This may be important when considering variable flows such as demand led systems relying on CO_2 or RH sensors.

It is clear that MVHR are not fit-and-forget systems. For any domestic system, the proper understanding and interaction of occupants is critical. Lack of knowledge about the nature and control of MVHR systems is likely to lead to poorly used or disabled systems. Whilst there are examples of good handover processes, this is not yet commonplace, in part at least because the understanding of the nature and performance of the system is not clear amongst designers, landlords and contractors. The system also needs to not cause nuisance to occupants in the form of noise or draughts. A critical element is ensuring firstly that there is clear understanding of the nature of the system and how it is supposed to be used by the procurement team, and secondly that robust mechanisms are in place for ensuring that occupants are given clear guidance in how to operate the system. Processes need to be available not just at early occupancy, but during changes in ownership or tenancy. Finally, a planned, legible maintenance regime will be needed for any house that has an MVHR system. For home owners this is an important aspect of the handover process. For tenanted properties, the landlord will need to evaluate who will be undertaking this maintenance, how frequent it will be, what access requirements are, and what the costs of this will be.

5 CONCLUSION

From this work and other literature it is clear that MVHR is becoming an increasingly widespread system in new energy efficient homes. For some construction approaches, particularly Passivhaus, it is standard practice. For houses built to the CSH standard, MVHR is also frequently used. Given the existing drivers for reducing energy and increasing airtightness, and emerging issues such as IAQ, it would seem likely that a solution that can provide good levels of ventilation, whilst providing heat recovery will continue to be an important component in contemporary low energy homes. Despite the issues outlined in the discussion, the performance data suggests that overall the use of MVHR systems can result in better levels of ventilation in comparison to naturally ventilated houses. The average CO_2 levels were reasonable; both average and peak levels were lower; and the environmental data suggests that more consistent temperature and relative humidity was achieved in dwellings with MVHR systems.

The overall picture that emerges from this study is that whilst there are some demonstrable benefits of MVHR systems, both in terms of ventilation and energy use, there are a number of significant risks. The tendency is for the construction industry is to take a low risk approach and to avoid, rather than to solve problems. In the context of the removal of CSH and Zero Carbon targets, it would be tempting to conclude that the risks outweigh the benefits. However the ability to provide good ventilation without consequential heat loss is an important goal in modern housing and its use in high performing standards such as Passivhaus require continual development and improvement. There are emerging issues, for example urban locations where pollution or noise may mitigate against window opening, where MVHR systems could have important benefits for health and well-being. It is therefore important that the insights gained from this study are used to improve standards and practice.

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